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A comparative analysis of current microbial water quality risk assessment and management practices in British Columbia and Ontario, Canada☆

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HIGHLIGHTS

- Canadian risk management and assessment practices diverge considerably from the literature.
- We found limited focus on microbial risk assessment for ecosystem health.
- Microbial risk assessment frameworks and management tools in Canadian provinces are variable.
- Different agencies use different risk tools, even within the same watershed.
- Metagenomics tools may address key limitations to current risk assessment and management.

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ABSTRACT

Bacteria, protozoa and viruses are ubiquitous in aquatic environments and may pose threats to water quality for both human and ecosystem health. Microbial risk assessment and management in the water sector is a focus of governmental regulation and scientific inquiry; however, stark gaps remain in their application and interpretation. This paper evaluates how water managers practice microbial risk assessment and management in two Canadian provinces (BC and Ontario). We assess three types of entities engaged in water management along the source-to-tap spectrum (watershed agencies, water utilities, and public health authorities). We analyze and compare the approaches used by these agencies to assess and manage microbial risk (including scope, frequency, and tools). We evaluate key similarities and differences, and situate them with respect to international best practices derived from literatures related to microbial risk assessment and management. We find considerable variability in microbial risk assessment frameworks and management tools in that approaches 1) vary between provinces; 2) vary within provinces and between similar types of agencies; 3) have limited focus on microbial risk assessment for ecosystem health and 4) diverge considerably from the literature on best practices. We find that risk assessments that are formalized, routine and applied system-wide (i.e. from source-to-tap) are limited. We identify key limitations of current testing methodologies and looking forward consider the outcomes of this research within the context of new developments in microbial water quality monitoring such as tests derived from genomics and metagenomics based research.

1. Introduction

Microbial risk assessment and management of water quality is an important concern and focus of governmental regulation and scientific inquiry (WHO, 2004). Microorganisms (bacteria, protozoa and viruses) are ubiquitous in aquatic environments. While most microorganisms are benign and serve essential ecosystem functions, some can be (or produce substances that are) harmful to ecosystem and human health. Microbially-contaminated drinking water has long been implicated in human illness and historically, attention has focused on finished (end-product or tap) water quality. However, these strategies are increasingly regarded as insufficient to prevent disease outbreaks and more attention has been paid to preventing illness from source-to-tap (Byleveld et al., 2008; Summerscales and McBean, 2011). Furthermore, it has

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been increasingly noted that poor microbial water quality can be harmful to aquatic organisms and ecosystem function (Gozlan et al., 2006; Miller et al., 2002, 2011; Weitz and Wilhelm, 2012). Human health and ecosystem health are implicitly related, particularly when considering microbial risk along the source-to-tap spectrum (Serveiss and Ohlson, 2007; Davies and Mazumder, 2003).

A comprehensive understanding of the risks (both existing and potential) to water quality can be achieved through evaluation of the entire water supply system. This concept is known as 'source-to-tap', whereby a high quality source, in combination with effective treatment and safe distribution, supported by legislation and ongoing water quality testing, will yield water that is safe for human consumption. As a cornerstone of drinking water quality risk assessment (Hrudey, 2011; Krewski et al., 2002), the source-to-tap framework has, to date, been mobilized with a focus on human health. Comprehensive risk assessment and management approaches that include the entire source-to-tap gradient are more likely to successfully address not only point-source pollution but also the more complex impact of non-point sources of water contaminants within a given watershed (Phillips, 1988). Sound risk assessment and management is crucial for both drinking water provision (Byleveld et al., 2008; Hamilton et al., 2006; Jayarante, 2008) as well as broader ecosystem protection (Serveiss and Ohlson, 2007). Indeed, risk management in a source to tap framework is thought to be critical given the recognition that hazards are innumerable and resources to deal with them are limited (Dominguez-Chicas and Scrimshaw, 2010; Gelting, 2009; Hamilton et al., 2006; Hrudey, 2004, 2009).

In Canada, some aspects of microbial testing for water quality are mandated across all jurisdictions (*Escherichia coli* and total coliform monitoring at tap for drinking water). However, beyond general guidelines recommending the adoption of a multi-barrier approach[1] by the Canadian Council of Ministers of the Environment Water Quality Task Group and the Federal–Provincial–Territorial Committee (CCME FPTC) on Drinking Water, there is no overarching Canadian framework specific to microbial risk assessment and management, anywhere along the source to tap framework (CCME, 2004). In the absence of a mandated national framework, considerable diversity in risk assessment and management of microbial water contamination exists across the country.

Little is known about the gap (or variance) between the theory and practical application of risk assessment and management. This study aims to address that gap by examining the ways different Canadian agencies and practitioners apply concepts and tools related to microbial assessment and management. Our objective is to describe current practices in two Canadian provinces, British Columbia (BC) and Ontario, and to situate them with respect to the literature and best practices. Our evaluation extends across the source-to-tap gradient and is attentive to both ecosystem and human health concerns. We do not attempt to compare or analyze the wide range of formalized risk assessment and management tools currently available. Rather we ascertain which ones, if any, practitioners are currently using. While we recognize the importance of chemical or other contamination risks, these considerations are beyond the scope of this study.

Our research included a literature review of current practices (see Section 2) and interviews with practitioners from selected agencies we expect are engaged in microbial risk assessment and management, from source-to-tap. Section 3 outlines the methods used. In the results (Section 4) we highlight key water quality monitoring issues as well as the considerable variability in risk assessment and management approaches between provinces and among agencies. In Section 5, we discuss current practices in light of best practices derived from the literature and find considerable divergence in on the ground practices. In Section 6, we consider the implications of these findings, particularly in light of recommendations in the literature for preventative, multi-barrier approaches that consider both ecosystem health and human health concerns. Looking forward we consider the outcomes of this research within the context of new developments in microbial water quality monitoring such as tests derived from genomics and metagenomics based research.

2. Risk assessment and management

The terms risk assessment and risk management are intrinsically linked and often conflated; however, their meanings are quite distinct. Risk assessment is a scientifically based process involving four key steps: hazard identification/assessment/measurement; hazard characterization (e.g. dose–response analysis); exposure assessment; and risk characterization (Hunter et al., 2003). Risk assessment undertaken within the context of a source-to-tap framework should offer an improved, integrated understanding of the various components of the water supply system, their strengths and weaknesses, and the existing and potential threats to water quality so that informed decisions can be made. Risk management refers to the control options, the legal considerations and risk management decisions (including economic and social factors) to reduce or mitigate risk. This includes the task of managing the assessed risks in the face of uncertainty, balancing consideration of potential hazards with available treatment and mitigation strategies as well as resources (Hamilton et al., 2006).

In many sectors risk assessment and management are central to operations and protocols. Although methods may vary, risk assessment and management practices have been utilized for decades in the energy utility sector, in industries such as automotive and food, and among High Reliability Organizations (HROs) such as aviation and nuclear power plants. Comparatively speaking, formalized, explicit and routine risk assessment practices in the water sector are relatively newer and less widespread (Egerton, 1996; Pollard et al., 2004).

In 2004, The World Health Organization (WHO) published their first set of guidelines emphasizing risk-based management of water (WHO, 2004). In doing so, the WHO advocated the application of broader, more comprehensive approaches to manage water quality challenges. This is indicative of a move away from a reactive approach of focusing on treated water (narrowly focusing on end-product testing at the tap), which can only highlight a potential health problem after the water has been consumed, toward a preventative risk management approach that looks comprehensively at the entire water system from the source-to-tap (Hrudey, 2003). Increasingly, preventative approaches are considered to be more reliable and cost effective to protect public health (Byleveld et al., 2008; Dominguez-Chicas and Scrimshaw, 2010; Hamilton et al., 2006). Coupled with this has been a transition from implicit (implied but not formally expressed) to explicit (formalized and routine) frameworks for risk assessment and management, particularly within the international water utility sector (Hrudey et al., 2006; Pollard et al., 2004; Summerill et al., 2010a). This is characterized by the introduction of procedures such as Hazard Analysis and Critical Control Points (HACCP), Qualitative Microbial Risk Assessment (QMRA) and Water Safety Plans (WSP). Table 1 provides a summary, with key citations, of several risk assessment tools currently available and in use.

Perhaps most notable of all these approaches is the WSP (based on HACCP and advocated by the WHO), which is a risk-based preventative approach to managing drinking water safety from catchment to consumer (source-to-tap). A WSP is an iterative process whereby the threats to the system; the capacity of the system to cope with threats; the ability to respond if barriers fail; and measures to improve the system are all characterized and incorporated into planning (Bartram et al., 2009; Gelting, 2009; Hrudey, 2011). As such, WSPs involve an explicit risk assessment and management philosophy (Hrudey et al., 2006; Pollard et al., 2004; Summerill et al., 2010a).

[1] The multi-barrier approach comprises of six core elements: source water protection; effective water treatment; secure water distribution system; water quality monitoring (at source, treatment plant, and tap); operator training and an emergency response procedure. Central to the multi-barrier approach is the assessment and management of the risks to water safety that can be addressed by each barrier.

Table 1
Selection of risk assessment & management tools identified in the literature.

Risk assessment tool	Brief description	Reference
Failure Modes and Effects (Criticality) Analysis (FME(C)A)	A systematic process to identify potential failure modes (causes and effects) based on experience with similar processes. (Widely used in manufacturing industries)	Dominguez-Chicas and Scrimshaw (2010), Hamilton et al. (2006), Pollard et al. (2004)
Critical Control Points (CCP)	A point, step or procedure (i.e. a critical failure area) that can be identified in a system. (Derived from FMEA)	Hamilton et al. (2006), Summerill et al. (2010a), Yokoi et al. (2006)
Hazard Analysis and Critical Control Points (HACCP)	A preventative risk management system in which a point, step or procedure (i.e. a critical failure area) can be identified in a system to which corrective actions can be applied so that a potential hazard can be prevented, eliminated, or reduced to an acceptable level. Also includes verification procedures to ensure the plan is adequate. (Builds on CCP. Originally developed in the food industry initially for NASA. Now widely used in food and pharmaceutical industries)	Davison et al. (2005), Dominguez-Chicas and Scrimshaw (2010), Hamilton et al. (2006), Miller et al. (2005), Pollard et al. (2004), Yokoi et al. (2006), Jayarante (2008)
Water Safety Plans (WSP)	Comprehensive risk assessment and management plan to identify and prioritize potential threats to water quality at each step in a specific system's water supply chain (from source to tap) implementing best practices to mitigate threats to drinking water. (Derived from HACCP and the multi-barrier approach)	Ashbolt (2004), Davison et al. (2005), Byleveld et al. (2008), Hamilton et al. (2006), Schijven et al. (2011), Smeets et al. (2010), Summerill et al. (2010a, 2010b), Vieria (2007), Yokoi et al. (2006), Jayarante (2008), Miller et al. (2005), Gelting (2009), Austin et al. (2012), Hrudey (2011), Bartram et al. (2009), Gunnarsdottir et al. (2012)
Total Quality Management (TQM)	A holistic, integrated management approach whereby all members of an organization participate in maintaining and improving processes, products, services. Also described as a cultural initiative that fosters a collaborative environment between departments within an organization to improve overall organizational quality.	O' Connor (2002), Hamilton et al. (2006), Hrudey (2003, 2004)
Quantitative Microbial Risk Assessment (QMRA)	A systematic quantitative assessment process to estimate the risks of human exposure to an array of microorganisms that can cause infectious disease outbreaks. Combines dose response information for the infectious agent with information on the distribution of exposures.	Haas et al. (1999), Ashbolt (2004), Ashbolt et al. (2010), Cool et al. (2010), Schijven et al. (2011), Signor and Ashbolt (2006), Smeets et al. (2010), Goss and Richards (2008), Benke and Hamilton (2008)
International Organization for Standardization (ISO) 14001 & 9001[a]	An internationally recognized family of certified standards approved through independent assessment. 14001 — Environmental Management: a systematic approach to minimize negative impacts, increase operational efficiency and identify cost savings, underpinned by continuous improvement. 9001 — Quality Management: a framework for an organization to focus on customer and product requirements, process performance and effectiveness in the systems delivery with a key focus on continuous improvement and objective measurement.	Serveiss and Ohlson (2007), Jayarante (2008), Miller et al. (2005), Summerill et al. (2010a), Vieria (2007)
Ecological Risk Assessment & Regional Risk Model	A process to evaluate the potential adverse effects of human activities on the ecological health of an ecosystem at a particular site. An explicit expression of the environmental value (species, ecological resource, or habitat type) that is to be protected.	Serveiss and Ohlson (2007)
Catchment Risk Management	Risk analysis of water supply at a catchment-scale. Considers a multitude of possible sources of hazardous events, caused by natural or human factors such as wild animals erosion, land use, industry, traffic, and recreational activities.	Miller et al. (2005)

[a] In addition, ISO standard for Risk Management (ISO 31000:2009) provides principles for effective risk management and corporate governance. However, unlike ISO 14001 and 9001, ISO 31000 cannot be used for certification purposes, although it does provide guidance for internal or external audit programs.

The uptake of explicit, formalized and routine risk assessment and management approaches in the water sector is gaining momentum around the world with a number of jurisdictions introducing policy and legal requirements. For example, the Dutch Drinking Water Act (2001) created a legal requirement for water utilities to use QMRA for drinking water from surface and vulnerable groundwater (Schijven et al., 2011). Water Safety Plans in particular are gaining popularity and are widely used across Europe, Africa and the Americas (Gelting, 2009). Iceland legislated drinking water utilities use Water Safety Plans in 1995 (Gunnarsdottir et al., 2012). The Australian Drinking Water Guidelines promote the implementation of Water Safety Plans in states and territories. For example, New South Wales has recommended water suppliers implement WSPs, and Victoria has regulated utilities to implement risk-based management plans through the Water Safety Act 2003 (Byleveld et al., 2008).

In Canada, it has been increasingly emphasized that a transition from implicit to explicit approaches in the area of water safety is necessary, particularly since the Walkerton crisis of 2000 and the report of the Walkerton Inquiry in 2002. Recommended approaches for securing drinking water include risk assessment and management, the source-to-tap approach, and WSPs (Ivey et al., 2006; Hrudey, 2011; O' Connor, 2002).

3. Methods

3.1. Rationale

To date, explicit material which links the theory of microbial assessment and management to actual practice is not readily available. In Canada, each province has a unique approach to water governance in general, and microbial risk assessment and management in particular. Key differences include regulatory requirements and provincial guidelines on risk assessment and management (Cook et al., in press; Ngueng Feze et al., under review). Furthermore, within a single watershed multiple stakeholders engage in microbial risk assessment and management including watershed authorities, water utilities and the health authorities. Because each agency has a distinct mandate, priorities and interests in water quality, we hypothesize that microbial risk management approaches will differ. We predict that health authorities and water utilities may prioritize risk assessment for human health (including drinking or recreational water), while watershed authorities will stress broader ecosystem health considerations in source water. We also expect important differences across these entities based on their mandates, data availability, and monitoring and assessment capacity. It is precisely these types of differences that have not been previously documented and that our study aims to uncover.

3.2. Selection of interviewees

The research employed a case study approach using semi-structured interviews to gather qualitative data (Yin, 2003; Summerill et al., 2010b; Taylor et al., 2013). In the two Canadian provinces studied (BC and Ontario) interviews were conducted with experienced personnel from select agencies to provide insights into "on-the-ground" risk assessment and management practices along the source-to-tap spectrum. Three case study watersheds were selected in each of the two provinces (Abbotsford, Kelowna and Victoria in BC and Toronto, Kitchener–Waterloo and Ottawa in Ontario). In each of the six watersheds, we examined the same three types of agencies that we anticipated would be actively engaged in microbial risk management (from source-to-tap): watershed authorities, water utilities and health authorities. Specific criteria for case study selection included type of: watershed (urban or mixed urban–rural); source water (lake, reservoir or river; areas served exclusively by groundwater sources were excluded); drinking water treatment (e.g. chlorination, UV and/or filtration); water purveyor management (e.g. municipal government, private utility); population served (e.g. medium (>10,000) to large drinking water systems (>90, 000)); and historical water quality or quantity challenges (Table 2).

3.3. Collection of data

Narrative data was collected through eighteen semi-structured interviews (conducted by telephone, lasting approximately 1 h) with practitioners employed in these agencies including water systems operators, municipal and provincial employees. This social science research approach enabled sufficiently open discussion with experienced practitioners to reveal nuances of microbial risk practices while ensuring interview discussions did not stray too far from the research objectives (Summerill et al., 2010a; Taylor et al., 2013). We sought to interview those with expertise in water management and policy, specifically individuals who would be most familiar with the day-to-day microbial risk assessment and management approaches engaged by these agencies. The narrative data presented here reflects the knowledge and opinions of the interviewees. Evidence of risk assessment and management practices and policies (such as HACCP or TQM reports) was not requested.

Twenty-three interview questions addressed four key themes: 1) how microbial risk is measured and assessed by the organization (including what data is collected, types of risk assessment tools used, and interpretation of results); 2) how the organization manages microbial risk (including risk management plans); 3) how risk is communicated (including sharing of information internally and externally with policy makers and other stakeholders); and 4) how policy and legislation affects 'on-the-ground' microbial risk management practices. The interviews were recorded, transcribed and qualitatively analyzed using theme codes (overarching issues) based on the questions asked of participants and sub-theme codes (specific points that fit within an overarching theme) derived from the content of the discussions. Free and informed consent of the participants was obtained; the study protocol was approved by the University of British Columbia, Vancouver, Canada, Behavioral Research Ethics Board (H12-01626, July 2012).

Table 2
Case study selection.

	Watershed authority	Water utility	Health authority
BC	Fraser Valley Regional District	Abbotsford	Fraser Health Authority
	Okanagan Basin Water Board	Kelowna	Interior Health Authority
	Capital Regional District Watershed	Victoria	Vancouver Island Health Authority
ON	Toronto Conservation Authority	Toronto	Toronto Regional Health Authority
	Grand River Conservation Authority	Kitchener–Waterloo	Waterloo Health Authority
	Rideau Valley Conservation Authority	Ottawa	Ottawa Public Health

4. Results

Four core themes emerged from the interviews: issues pertaining to water quality monitoring; limited and variable application of risk assessment tools; limited use of risk management plans; and significant differences in risk assessment practices across the two study provinces.

4.1. Water quality monitoring

Water quality monitoring is the first step toward microbial risk assessment and management (characterization and measurement of the hazard). In both provinces water utilities are the primary collectors of microbial water quality data, often (but not always) sharing the test results with health authorities and watershed authorities. Some health authorities and watershed authorities conduct/enforce microbial sampling, but the extent and drivers for undertaking their own sampling are highly varied.

4.1.1. Microbial monitoring

E. coli and total coliforms are the most commonly measured microbial water quality indicators in accordance with legislated requirements (BC Reg. 200/2003 Drinking Water Protection Regulation; O. Reg. 169/03 Ontario Drinking Water Quality Standards), followed by indirect measures (primarily water treatment process indicators) such as turbidity and chlorine residual. All six water utilities test for *E. coli* and total coliforms and they are legally required to provide these test results to the health authorities. (Health authorities in turn may undertake their own additional microbial sampling). Sampling type and frequency vary between types of agency interviewed and between provinces (on provinces see Cook et al., in press). Unlike Ontario, BC's drinking water quality regulation does not prescribe regularity or sample types (see Table 3). Five of the 18 agencies interviewed (from both BC and Ontario) monitor for specific pathogens, typically testing for *Giardia* and *Cryptosporidium*. Across both provinces a few agencies (usually water utilities) occasionally undertake additional testing such as Microscopic Particulate Analysis (MPA) (as a surrogate of protozoa), enterococci bacteria, *Bacteroides* and bacteriophage, but this testing is not performed routinely.

4.1.2. Human health focus

Of the three agency types interviewed watershed authorities are the only ones to explicitly include both the protection of human and ecosystem health as part of their mandate. However, not all watershed

Table 3
Comparison on microbial risk assessment and management approaches at the provincial scale.

	British Columbia	Ontario
Microbial water quality standards	No total coliforms, *E. coli*, or fecal coliforms (B.C. Reg. 200/2003 Drinking Water Protection Regulation)	No Total coliforms or *E. coli* (heterotrophic plate counts) (O. Reg 169/03 Ontario Drinking Water Quality Standards)
Legislated sampling frequency	Population-based; no regularity prescribed; sample type not specified	Population-based; regularity prescribed; sample type specified
Centralized data collection	No — there is no centralized or provincial water quality database.	Yes — a centralized system for province-wide water quality data is collected and maintained by the Ministry of Environment.
Multi-barrier approach	Voluntary approach — provincial guidelines for the multi-barrier approach have been established.	The multi-barrier approach is regulated through several provincial laws, incl. Safe Drinking Water Act and the Ontario Water Resources Act, Clean Water Act.
Source water protection	Part 5 of the BC Drinking Water Protection Act (BC DWPA) and Regulation (BC DWPR) enables Drinking Water Protection Plans to be developed, but these are not compulsory. Other regulatory tools with powers to protect source waters include: Water Act, Forest and Range Practices Act, Environmental Management Act and Land Act.	Clean Water Act, 2006, S.O., 2006, c.22 mandates source protection planning for municipal water sources (untreated surface or groundwater).
Risk assessment	• No legislative imperative to conduct drinking water quality risk assessment, unless a Drinking Water Officer orders a source water or system assessment (DWPA 2001s.18). • No consistent risk assessment and risk abatement methodologies for drinking water quality or ecosystem health.	Formal risk assessment (of drinking water sources are required in accordance with the province's Safe Water Act 2002). Safe Drinking Water Act 2002s.15(1).
Risk management	• No legislative imperative to conduct drinking water risk management. • No consistent risk management methodologies. • Emergency Response procedures are required under (DWPA 2001s.10).	Required by legislation Clean Water Act, 2006 287/07, 54–60 (this includes Emergency Response Procedures).

authorities engage in microbial water quality monitoring in line with this mandate. One Ontario watershed authority interviewee commented that since the Walkerton tragedy watershed authorities are somewhat behooved to include *E. coli* in their examination of water quality but cautioned how this information can be used, interpreted and shared. Microbial data have limited utility when collected through infrequent grab samples; without routine year-round sampling, this data cannot be incorporated into most microbial risk assessment tools. Since water quality monitoring for human health falls under the jurisdiction of other agencies (water utilities and health authorities), three interviewees indicated the futility of collecting microbial water quality information, particularly when information is collected more rigorously by other agencies. As such, watershed authorities may only use microbial information to better understand the overall state of the watershed, rather than inclusion in formalized microbial risk management. In the absence of this information some watershed authorities indicated that they tend to focus on chemical contamination, which they felt they had a better capacity to monitor.

4.1.3. Limitations of current testing approaches

The availability of suitable tools to characterize microbial risk is essential for successful risk assessment and management. Interviewees shared five key underlying concerns related to microbial data collection. First, they indicated concern about their limited ability to detect specific pathogens, particularly the absence of tools to detect viruses in water. The limitations of using *E. coli* as a surrogate indicator for all pathogens were specifically highlighted, since strong empirical evidence indicates that *E. coli* is not always predictive of pathogens occurrence, particularly for viruses and protozoa. I.e. the absence of *E. coli* is not a guarantee that a water sample is pathogen free (Harwood et al., 2005; Leclerc et al., 2001). Second, interviewees expressed concern related to the inability to identify the source of contamination with certainty. Currently, practitioners can target only the most likely species that may be a cause for concern with inadequate resolution, which interviewees indicated is an ineffective use of limited resources. Third, is concern regarding the time delay between collecting a sample and receiving the test results, highlighting the challenge to protect public health when water advisories depend on culture-based testing results that take 18–24 h to generate (without consideration for transport time to the laboratory). The time lag was identified in both recreational and drinking water quality contexts and is also highlighted in the literature (Hrudey, 2004, 2011; Hamilton et al., 2006; Vieria, 2007; Gelting, 2009). The fourth concern is the inability to establish whether a particular microorganism will cause disease in humans (i.e. some methods cannot distinguish between pathogenic and non-pathogenic strains). Fifth, interviewees noted the inherent variability of sampling and testing methods between agencies, which may impede data sharing.

Together, these five concerns emphasize ongoing challenges for agencies engaged in characterizing microbial risk. It is clear across the range of agencies interviewed that legislated indicators alone are insufficient for assessment and microbial risk management needs and as such, additional microbial tests are being applied. Interviewees emphasized a desire for microbial tests with quicker turn-around-times and that answered specific risk associated questions (e.g. whether a microorganism is pathogenic to humans or whether groundwater is vulnerable to pathogen intrusion).

4.2. Limited and variable use of risk assessment

Risk assessment practices across the 18 agencies interviewed are limited and variable in terms of type of methods used, scope of application and frequency of use.

4.2.1. Types of risk assessment methods used

Among our case study agencies there appears to be limited uptake of the established formalized methods as identified in Table 1. In some cases, interviewees reported little awareness of such tools. Of the methods and tools identified in Table 1, HACCP & CCP were the most commonly identified or familiar to our interviewees; however, the full implementation of these methods is limited. Instead, interviewees indicated they typically use existing tools informally; drawing on elements of these tools (particularly HACCP) to develop their own tailor-made risk assessment better suited to their needs or resource capacities (financial and staff). Interviewees in both provinces identified a number of constraints to their ability to practice microbial risk assessment and management. These include: insufficient data collection to “do justice to a risk assessment”; financial and staff capacity (to collect more data more frequently, conduct specific microbial risk assessment projects or to introduce an industry standardized tools such as HACCP or ISO certification); limited regulatory requirements (e.g. there are no regulated standards for *Cryptosporidium*); and lack of tools (e.g. to assess microbial risks to groundwater).

Only two of the 18 agencies (both in Ontario) use QMRA routinely. One application is by a health authority for beach (recreational) water quality purposes and the other is by a water utility. Both agencies acknowledged the technical support provided by Health Canada in their implementation of QMRA. One Ontario water utility interviewee indicated that the absence of provincial funding limited the capacity of practitioners to use QMRA; instead collaboration with academic researchers was driving its use in municipalities. Two watershed agencies (both in BC) conduct ecological or environmental risk assessments: one includes microbial water quality data and the other focuses only on chemical risk. Challenges to conduct ecological risk assessments on a watershed scale identified by the interviewees (mentioned in Sections 4.1.2 and 4.1.3) are found in the literature (Serveiss and Ohlson, 2007).

4.2.2. Scope and frequency of application

Risk assessments that are formalized, routine and applied system-wide have not been widely adopted by the agencies interviewed, other than the Ontario water utilities, which conduct these from source-to-tap. The most common applications of risk assessments are short-term or one-off assessments. For example, prior to design and construction of a water treatment plant or a project specific assessment might be undertaken to examine one particular component of the entire water system (e.g. recreational water quality at a certain beach, or until engineering controls for a specific contamination source could be established). No one reported using any of these models explicitly for ecosystem health.

4.3. Limited use of risk management plans

Ten interviewees noted that their agency does not have any formal risk management plan in place for human health or ecosystem purposes, including all six watershed authorities in BC and Ontario. As one BC water utility interviewee observed, "…from the point the water enters the intake, down to the customer's tap, we do not have a risk management process. Not an explicit one certainly." Of the agencies that stated they do have a risk management plan the extent of these were varied and often project specific (e.g. requirement for filtration deferral). Only one agency identified having ever used a specific microbial risk management plan, for groundwater under direct influence of surface water; however, the interviewee noted that they no longer use this method.

While many of the interviewees acknowledged their agency does not have a formalized risk management plan for microbial risk, all water utilities and health authorities have a formal Emergency Response Procedure (ERP), which is a regulatory requirement in both BC and Ontario. These procedures are activated once an actual (e.g. *E. coli* present in treated water) or perceived (e.g. elevated total coliform count or turbidity measurement) microbial contamination event occurs and typically includes a communication strategy. In line with this finding, a few interviewees suggested that their current approach to risk assessment or management is reactive.

Interestingly, despite the absence of microbial risk assessment practices, there is general confidence among the agencies interviewed (13 out of the 18 interviewees) that they are well positioned to handle a microbial contamination event. This confidence could be attributed to a variety of factors including: i) having formalized response and communication procedures in place (some municipalities have designated crisis management teams); ii) routine monitoring at least at the tap (continuous monitoring in the water treatment plant or compliance monitoring as required by legislation); iii) land ownership around source waters (particularly the ability to exert control over source water protection); iv) system knowledge (such as lessons learned from previous incidents); and v) having a contingency plan in place to augment their water supply.

4.4. Differing provincial approaches to risk assessment and risk management

Ontario and BC have fundamentally different governance approaches to the application risk assessment and management (see Table 3).

Ontario legislation requires that operators of municipal water systems conduct microbial risk assessments and all three of the Ontario water utilities interviewed confirmed they conduct formal microbial risk assessment in accordance with the Ontario's Safe Drinking Water Act 2002s.15(1). This legislation requires municipal drinking water systems operators to prepare operational plans according to the Director's directions. The directions prescribe a Drinking Water Quality Management System (DWQMS) specifying minimum requirements for risk assessment and risk management in operational plans (Schedule A). As one Ontario water utility interviewee described, "It's a pretty legislated regulatory environment that we function in." Indeed, penalties for non-compliance are onerous; as of January 2013 water system owners and operators in Ontario bear personal responsibility (financial penalties and/or imprisonment). In contrast, BC has no legislative imperative; a drinking water officer may require a BC water utility to undertake but this is discretionary. Only one of the three BC water utilities interviewed acknowledged using a formalized risk assessment and management approach, which was a requirement to obtain a filtration deferral for water treatment. None of the BC water utilities undertakes formal microbial risk assessment or management on a routine basis. One interviewee observed, "the expectations [in BC] are not as high [in comparison with Ontario], so they are not difficult to meet. In terms of drinking water health, in most other jurisdictions… there is more stringent management within the regulation."

Given the small sample size, we can only suggest that indeed the regulatory differences between the two provinces appear to have an important impact in terms of the microbial risk practices being undertaken by these agencies. We discuss these key provincial differences in Section 5.1.

5. Discussion

There are several axes of variability that emerged as important in the analysis: 1) approaches to microbial risk assessment and management are variable between provinces; 2) water utilities, health authorities and watershed authorities approach, and may be required to approach, risk assessment and management differently; 3) risk assessment and management practices (particularly in BC) diverge from the literature on best practices in ways that are potentially significant; 4) there is limited, if any, focus on risk assessment for ecosystem health from the microbial perspective and 5) testing method limitations.

5.1. Varying approaches between provinces

British Columbia and Ontario have notably different water governance frameworks. In response to recommendations in the Walkerton Inquiry (O' Connor, 2002), Ontario overhauled their water governance approach. A strong legislative and regulatory framework was introduced with a source-to-tap focus, and includes risk management protocols to enforce and harmonize approaches across the province (Jayarante, 2008; O' Connor, 2002). Specifically, Ontario is the first province in Canada to introduce a legislated, semi-quantitative risk assessment framework for source water protection. As one Ontario water utility interviewee described, "We have a multi-barrier approach and in fact it is now enshrined in legislation".

In contrast, legislated requirements in BC are narrower in scope; the BC approach to source protection might best be described as voluntary (see part 5 of the BC DWPA). Moreover, the BC DWPA and its regulations (see Table 3) are outcome-based in that they specify the outcomes to be achieved, not how to achieve them. BC does have provincial guidelines for the multi-barrier approach, but none explicitly for risk assessment and risk management. Some BC interviewees attributed confidence in their water quality to their ability to protect their source water (either through limited land use activity or fully protected watersheds). Indeed, BC's topography lends itself more easily to source protection with approximately 60% of the province's population receiving water from protected watersheds (including the cities of Vancouver and Victoria). However, despite the fact that fully protected watersheds serve more than half the population, BC has the highest number of boil water advisories per capita (Eggerston, 2008). Furthermore, the province has also had the highest rate of enteric (gastrointestinal) infections of all the Canadian provinces, a proportion of which may be attributable to waterborne transmission (Isaac-Renton et al., 2003). Historically, BC water supplies have not always been safe and highlight that a perception of pristine water province-wide may actually undermine risk management to the extent that this perception may contribute to the lack of preventative practices.

5.2. Varying approaches between watersheds and similar agencies

Few clear patterns emerge in terms of type, methods, scope and frequency of risk assessment and management between agencies with similar mandates. Our results show that in our two case provinces, between watersheds and between agencies (even of the same type) risk assessment and management practices vary widely. While watershed authorities typically focus on overall watershed characterization and assessment (using environmental, ecological or regional risk assessment tools, but not always including microbial pathogens), health authorities and water utilities focus primarily on drinking water supply using TQM based tools, which incorporate elements of HACCP and CCP. Not only does the scope and frequency of microbial risk assessment vary but so do the methods applied. No single tool has been adopted widely. Agencies that do practice risk assessment often prefer to develop their own tools. None of the agencies studied have pursued formal certification (e.g. ISO 9001 and 14001), citing limited capacity (financial and staff) as an impediment.

5.3. Limited focus on ecosystem health

There is limited evidence in the literature that ecosystem-focused risk assessments are routinely incorporated into water risk assessment and management activities (Pollard and Huxham, 1998). Serveiss and Ohlson (2007) argue that in Canada water quality standards are human-centric and watershed planning is oriented toward drinking water quality protection, focusing primarily on chemical and physical measures, omitting a broader ecosystem perspective. A truly integrated source-to-tap risk management approach should emphasize both human and ecosystem health. The concept of integrating human and ecological risk assessment has been advocated in the environmental literature (Harvey et al., 1995; Sekizawa and Tanabe, 2005; Scott et al., 2005) but only applied infrequently to aquatic environments (Moiseenko et al., 2006; Orme-Zavaleta and Munns, 2008; Wang, 2006). Moreover, in the literature, ecological risk assessments for aquatic environments have focused largely on chemical risk assessment, rather than microbial risk assessment (Brock, 2013; Ellis, 2000; González-Pleiter et al., 2013; Leeuwangh et al., 1993). An integrated risk management approach is consistent with the “One Health” approach advocated by organizations such as the WHO and the World Organization for Animal Health: that environments, animals and humans health are interrelated in a complex system with many common stressors. An integrated approach allows for a broader, system-wide approach to managing microbial risks and creates efficiencies by using common sets of tools for risk characterization, assessment and management. Consider the example of an algal bloom: algal toxins are harmful to mammals (human, aquatic and terrestrial mammals) and the bloom can also change nutrient and gas cycling in the ecosystem resulting in adverse outcomes at multiple trophic levels in the ecosystem. Here, ecosystem and human health are clearly connected and could benefit from an integrated approach.

In our case study entities, we find ecosystem risk assessments are largely absent and, when present, are not integrated with human health risk assessments. Even in large water utilities, which have both watershed and drinking water departments, we found little integration of ecosystem and human health assessments, and minimal emphasis on the microbial dimensions of ecosystem health in general. Even within the same organization, different tools are being used in ways that can serve as an obstacle to integration. One interviewee from BC postulated that ecosystem health is on the whole poorly understood. He observed, “one of the biggest problems I think we have is the assumption that we can treat something, therefore, we don't have to worry so much about the quality of the source. I think there needs to be a strong connection between the quality of the source and what's coming out the pipe. I don't think that we want to promote the notion that we can — we should allow the degradation of the source simply by increasing the treatment. So an emphasis on watershed planning, on controlling non-point sources, on people knowing how their actions affect the quality of the source and how that relays into cost savings in terms of treatment.”

5.4. Divergence from literature on best practice

On the whole, our research also indicates that current approaches to microbial risk assessment and management in BC case study sites, and to a lesser degree in Ontario, remain largely reactive. Formal microbial risk assessment and management practices are not widely adopted across agencies; they are not typically carried out on a continuous basis (but rather on an ad hoc, as needed basis); and they are not carried out across the full water system from source to tap, rather components of the system (e.g. focusing only on the treatment dimensions, rather than incorporating quality of source water as well). Evidencing a reactive risk management pattern, agencies indicated that risk assessments are typically instigated after a contamination event. While ERPs have an essential role, these are best thought of as reactive approaches. A broader proactive approach as advocated by the WHO would require microbial hazard identification and efforts to prevent and remediate contamination events. We find that in BC in particular microbial risk assessment and management approaches for water quality have not yet achieved the vision of the WHO. Internationally and in Canada, despite the emphasis on source protection, ecosystem health appears to be a lower priority. Economic and political factors; assumptions made is risk assessment scenarios; and other factors can enable or constrain microbial risk assessment and management practices (see Reimann and Banks, 2004). Further work on why microbial risk might not be pursued, or complex tradeoffs with other human and ecosystem health considerations would be a fruitful avenue for future exploration.

We postulate that the regulatory context in Ontario is having some impact on actual practices of risk assessment and management. Although not as extensively as we might expect to be able to more adequately integrate human and ecosystem approaches, or to share data across agencies. In terms of other important trajectories toward the adoption of more integrated and explicit approaches, it is also worth noting that the Canadian province of Alberta is introducing a legal requirement for drinking water safety plans by December 2013; but again, this will likely focus on human health rather than an integrated risk management approach.

5.5. Limitations of current testing methodologies

The success of microbial risk assessment and management is only as good as the available risk characterization or measurement tools. In addition to identifying gaps in current approaches to risk assessment and management, our research highlights key limitations to current microbial testing methods, a critical first step in risk assessment and management. As discussed in Section 4.1.3, interviewees were most concerned with the turn-around-times and suitability of current tools to enable comprehensive and routine microbial risk assessment. While all microbial classes (bacteria, protozoa and viruses) are harmful to ecosystem and human health, most of the available tools are narrow in range, targeting only bacterial pathogens (Davison et al., 2005). As noted, some interviewees identified the need for additional testing parameters to enable thorough risk assessment and risk management.

Developments in genomics and biotechnology may resolve some of the methodological limitations to risk characterization identified by interviewees. For example, water metagenomics studies may identify new targets for microbial testing, which may allow risk characterization along a wider, and more representative, set of microbial parameters (Thomas et al., 2012; Languille et al., 2012). Current risk characterization approaches rely on detection of microbial indicators, which do not accurately predict the occurrence of all bacterial, viral and protozoan pathogen, while pathogen specific testing is cost prohibitive and lack the sensitivity required for adequate risk characterization. Novel markers that could better predict the occurrence of bacterial, viral and protozoan pathogens would improve risk assessment and management activities.

Furthermore, biotechnology advancements in testing platforms will likely allow more sensitive assays (lower limits of detection), faster turn-around-times, identification of contamination source, and are expected to be available in the near future at equal or lower costs. For example, quantitative real-time polymerase chain reaction (qPCR), which detects the nucleic acid of a microorganism rather than culturing organisms, provides the benefit of being able to detect even organisms that cannot easily be cultured such as viruses, protozoa and some difficult to culture bacteria. This platform can test nearly any microbial target, is flexible (new assays can easily be developed) and is widely applied in clinical diagnostics. We see considerable potential for new markers on new qPCR platforms to be integrated into current risk assessment and management approaches. Novel tests that are more sensitive and specific have the potential to significantly improve microbial risk assessment and management capacities. It should be noted, however, that nucleic acid based approaches like qPCR do have methodological limitations, such as challenges with compounds that may inhibit the assay or detection of dead cells. Technical advancements have addressed many of these technical challenges and are detailed by others (Girones et al., 2010; Aw and Rose, 2012).

6. Conclusions

In sum, our research identifies considerable variability in risk assessment and management frameworks currently applied in BC and Ontario. We find that the variability between and within provinces, as well as between agencies, is indicative of an overall lack of a uniform approach. We find that the most common applications of risk assessments are short-term or one-off assessments. Risk assessments that are formalized, routine (or continuous) and applied system-wide (i.e. the entire water supply system — source-to-tap) have not been adopted widely. Our findings of varied approaches between and within provinces are broadly consistent with the literature on water governance in Canada, which indicates considerable fragmentation, and that water management is often ad hoc (Bakker and Cook, 2011; Hill et al., 2008; Hrudey, 2011; Weibust, 2009). We also observe that ecological risk assessment is largely absent among the entities interviewed. Our research suggests that current approaches to microbial water quality are still largely implicit and reactive, diverging from the literature on best practices in the water sector.

The literature suggests the need for preventative and explicit risk management for the protection of both human and ecosystem health, but our case study provinces fail to meet these best practices in a comprehensive manner. In terms of significance, this work highlights the need for improved microbial risk assessment and management frameworks in Canada. At a minimum, data needs to be comparable and integrated, and resources and expertise need to be shared in order to overcome some of the issues identified by interviewees. Adoption of improved microbial testing, based on genomics and biotechnological advances, would provide richer data, faster, and improve risk assessment and management. As well, we see considerable scope to more adequately evaluate the importance of different regulatory frameworks, either in terms of actual risk management practices, or better still, linkages to human and ecosystem health outcomes. In the absence of considerable progress toward these ends, human and ecosystem health may continue to be compromised.

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